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While many studies have been conducted on metamaterials at microwave frequencies, comparatively few have examined their use in high-power applications. Here, we perform a general study of metamaterial geometries to identify configurations that are well-suited for utilization in high-power environments. We further develop a genetic algorithm optimization scheme for synthesizing pixelized geometries with artificial magnetic conducting (AMC) properties and reduced maximum field enhancement factor (MFEF).

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High-Power Considerations in Metamaterial Antennas

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***Abstract*—While many studies have been conducted on metamaterials at microwave frequencies, comparatively few have examined their use in high-power applications. Here, we perform a general study of metamaterial geometries to identify configurations that are well-suited for utilization in high-power environments. We further develop a genetic algorithm optimization scheme for synthesizing pixelized geometries with artificial magnetic conducting (AMC) properties and reduced maximum field enhancement factor (MFEF).**

I. Introduction

Frequency-selective surfaces (FSS) are closely related to metamaterials in their use of subwavelength periodic structures to generate a desired electromagnetic response. FSS designs are evaluated and specified on their scattering responses (magnitude and phase), rather than an effective material response. However, high-power considerations are essentially the same between metamaterials and FSS designs. Through investigation of FSS structures for high-power applications, it was found that the limiting factor for power handling in most designs was dielectric breakdown in the FSS due to enhanced field strengths inside the structure compared to the free-space energy density. Dielectric breakdown is a temporary effect that changes the operation of the device and can also cause physical damage. The enhanced field strength in an FSS or metamaterial may be quantified by the maximum field enhancement factor (MFEF), which is the ratio of the peak field within the structure to the incident field. Several FSS designs have been evaluated in the literature on the basis of the MFEF [1,2].

II. Survey of Metamaterial Geometries for High-Power RF Applications

Metamaterials are designed based on their effective material parameters, and can achieve properties that do not exist in nature (*e.g.*, negative index metamaterials (NIM), zero/low index metamaterials (ZIM/LIM), and high index metamaterials (HIM)). Metamaterials with unit cells that support a confined resonance, such as most NIM and LIM, can have significantly stronger electric fields than the incident wave, which can cause dielectric breakdown either in the air or the substrate material. Thus, controlling the resonant effects of the metamaterials is a key factor for enabling high-power microwave (HPM) design. Some metamaterials may be modified to reduce the field enhancement factor while maintaining the desired response.

A typical NIM design will exhibit high absorption losses and high field enhancement factors near the resonance, which limits its application for HPM. However, a modified fishnet structure [3] demonstrates a greatly reduced MFEF, particularly at the NIM and ZIM bands. Compared with a typical split-ring resonator (SRR) design, we have demonstrated that the MFEF of a modified fishnet at the NIM band (n = -1) was reduced from 18 to 7.6, and at the ZIM band (n = 0), the MFEF reduces from 11.5 to 7.0.

ZIM and LIM, although resonant like the NIM devices, operate in the tail of the resonance and will have reduced loss and MFEF compared to a NIM. ZIM/LIM have been widely used for antenna beam collimation and the construction of high-aperture-efficiency antennas [4,5].

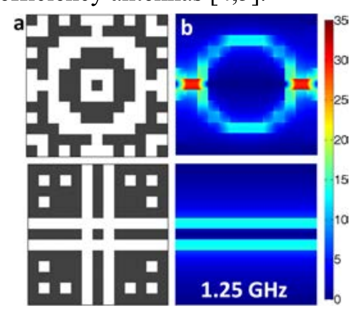

Fig. 1 (a) Unit cell geometries with AMC band at 1.25 GHz. (b) E-field enhancement at 1.25 GHz. (top) and (bottom) are Design 1 and Design 2, respectively.

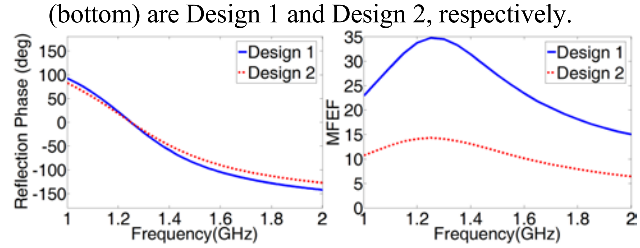

Fig. 2. Simulated (a) Reflection phase and (b) MFEF for the two designs shown in Fig. 1.

III. Genetic Algorithm Synthesized Artificial Magnetic Conducting Surfaces for High-Power

High impedance surfaces (HIS) comprise another type of metamaterial that is used primarily in low-profile antenna systems [6]. Such a structure consists of a FSS-type screen supported by a dielectric substrate and a ground plane and forms a resonant cavity that can couple with incident

electromagnetic waves to mimic an artificial magnetic conductor (AMC) response at resonance, where the reflected wave is in-phase with the incident wave (*i.e.* the reflection phase is zero degrees). Many studies have been conducted on HIS to improve bandwidth, weight, and even to design custom multi-band responses using genetic algorithm (GA) optimization [6]. Here, we examine the suppression of the MFEF during the GA synthesis of the HIS geometry.

TABLE I. OPTIMIZED HIS DESIGN PARAMETERS.

	Unit Cell Size	Substrate Thickness	Substrate Permittivity
Design 1	5.00 cm	1.75 cm	2.00
Design 2	4.86 cm	2.00 cm	2.00
Design 3	7.09 cm	1.52 cm	7.76
Design 4	6.62 cm	1.49 cm	11.59

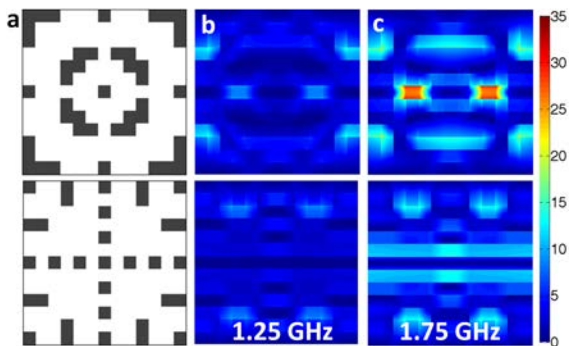

Fig. 3. (a) Unit cell geometries with AMC bands at 1.25 GHz and 1.75 GHz. (b) E-field enhancement at 1.25 GHz and (c) 1.75 GHz. (top) Design 3 and (bottom) Design 4.

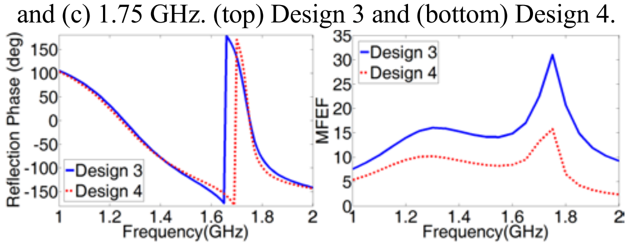

Fig. 4. Simulated (a) Reflection phase and (b) MFEF for the designs shown in Fig. 3.

Genetic algorithms (GA) are robust stochastic optimizers that operate based on the Darwinian theory of evolution [7]. In order to synthesize the HIS structure, the design parameters including the unit cell size, substrate thickness, substrate permittivity, and pixelized geometry are encoded into a binary chromosome to be optimized. A *Cost* function is also defined to measure the performance of each design. The *Cost* function used for single or multi-band AMC surfaces is given by

$$Cost = \sum_{freqs}\{\varphi_R - 0.0\}^2 \qquad (1)$$

where φ_R is the reflection phase in degrees and *freqs* are the frequencies where an AMC condition is desired. The GA was used to synthesize a HIS with an AMC condition at 1.25 GHz as shown in Fig. 1 with the design parameters given in Table I. The reflection phase shown in Fig. 2 has the desired value of 0 at 1.25 GHz. However, the MFEF also has a peak value of 34.7 at the same frequency.

In order to reduce the MFEF at resonance, the *Cost* function was modified to include a calculation of the MFEF in the plane of the FSS elements. The modified *Cost* function is given by

$$Cost = \sum_{freqs}\{\varphi_R - 0.0\}^2 + \{\max(|E|) - 0.0\}^2 \qquad (2)$$

where $|E|$ is the magnitude of the electric field in the plane of the FSS elements. Using this *Cost* function, a second design was synthesized as shown in Fig. 1. This design also has an AMC condition at 1.25 GHz, but the MFEF stays under 14.3 as shown in Fig. 2. This demonstrates that by optimizing for a minimum MFEF, a reduction of 58.8% in peak MFEF was achieved at resonance.

For single band designs, other intuitive FSS elements could be explored for reduced MFEF, but GA optimization is particularly useful for achieving more complex design criteria, such as multi-band responses. A second pair of designs was optimized for dual AMC bands at 1.25 GHz and 1.75 GHz as shown in Fig. 3 using *Cost* functions (1) and (2), respectively. The reflection phases for these two HIS are plotted in Fig. 4 illustrating that both designs achieve an AMC condition at the prescribed frequencies. However, the MFEF curves shown in Fig. 4 reveal that the peak MFEF has been reduced from 31.0 to 15.8, or by 49%, when also optimizing for low MFEF.

IV. CONCLUSIONS

A study of metamaterial geometries for HPM applications was presented in this paper. A survey of the MFEF in geometric elements for negative and zero index metamaterials was conducted to identify structures that are well-suited for use in HPM applications. Also, a technique for optimizing pixelized HIS with reduced MFEF by utilizing genetic algorithms was presented. By employing the proposed GA optimization scheme, HIS were synthesized with MFEF reduced by approximately 50%.

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REFERENCES

[1] M. Al-Joumayly and N. Behdad, “A new technique for design of low-profile, second-order, bandpass frequency selective surfaces,” *IEEE Trans. Antennas Propagat.*, vol. 57, no. 2, pp. 452 –459, Feb. 2009.

[2] M. Li and N. Behdad, “Frequency selective surfaces for high-power microwave (HPM) applications,” Proceedings of the *2012 IEEE Antennas and Propagation Society International Symposium*, pp. 1 –2, 2012.

[3] Z. Jiang, J. A. Bossard, and D. H. Werner, “Low loss RF modified fishnet metamaterials with optimized negative, zero and unity refractive index behavior,” Proceedings of the *2009 IEEE Antennas and Propagation Society International Symposium*, pp. 1 –4, 2009.

[4] Z. H. Jiang, M. Gregory, and D. H. Werner, “Experimental demonstration of a broadband transformation optics lens for highly directive multibeam emission,” *Physical Review B*, vol. 84, pp. 165111/1–6, Oct. 2011.

[5] J. P. Turpin, Q. Wu, D. H. Werner, B. Martin, M. Bray, and E. Lier, “Low cost and broadband dual-polarization metamaterial lens for directivity enhancement,” *IEEE Trans. Antennas Propagat.*, vol. 60, no. 12, pp. 5717 –5726, Dec. 2012.

[6] D. J. Kern, D. H. Werner, A. Monorchio, L. Lanuzza, and M. J. Wilhelm, “The design synthesis of multi-band artificial magnetic conductors using high impedance frequency selective surfaces,” *IEEE Trans. Antennas Propagat.*, vol. 53, no. 1, pp. 8-17, Jan. 2005.

[7] R. L. Haupt and D. H. Werner, Genetic Algorithms in Electromagnetics, Wiley, Hoboken, NJ, 2007.